Influence of Zn doping profiles on excitation dependence of photoluminescence intensity in InGaAsP heterostructures

D.K. Young, C.L. Reynolds Jr., V. Swaminathan and F.S. Walters

It is known that the Zn doping profile in strained multi-quantum-well (MQW) InGaAsP lasers strongly affects the electro-optical characteristics of these devices and their temperature sensitivity. A systematic investigation of the excitation dependence of the active layer photoluminescence (PL) intensity from compressively strained InGaAsP MQW *pin* laser material with different Zn doping profiles is described. When the *pn* junction lies within the active region, the excitation dependence of the PL intensity is superlinear at low excitation and linear at higher excitation. As the Zn profile is set back from the heterointerface creating a displaced *pn* junction from the active region, the excitation dependence is superlinear and linear at 300 K but becomes linear for all excitation powers at 77 K. The implications of these observations are discussed.

While the technological success of strained, multi-quantum-well (MQW) InGaAsP lasers for telecommunications is well known, it is also recognised that the performance of these lasers is strongly influenced by the acceptor, normally Zn, doping profile [1–6]. The temperature sensitivity is especially affected by the doping profile. There is a trade-off between electron leakage from the active region and internal loss. An increased Zn concentration at the heterointerface (HI) reduces leakage for improved high temperature and high frequency performance. However, increased Zn in the active region results in increased optical loss and subsequent higher threshold current and lower slope efficiency [2, 5, 6]. Thus, it is of considerable interest to understand the *pn* junction characteristics of InGaAsP MQW laser material non-destructively.

The excitation dependence of the active region photoluminescence (PL) has previously been shown to be a suitable technique by which one can investigate the materials characteristics of AlGaAs laser wafers with different Be profiles [7]. In particular, Swaminathan *et al.* [7] reported that, when the Be profile had penetrated into the *n*-cladding layer of MBE-grown AlGaAs lasers, the excitation dependence of the PL intensity became linear for all excitation powers. In this Letter, we extend this technique to investigate the excitation dependence of the MQW PL intensity from compressively strained InGaAsP MQW *pin* laser material with different Zn doping profiles. In the presence of a *pn* junction, the radiative intensity varies superlinearly and then linearly with excitation power. When the Zn profile is set back from the heterointerface into the *p*-cladding layer, the intensity varies linearly for all excitation powers at 77 K, a behaviour which is similar to that of an isotype heterostructure [7].

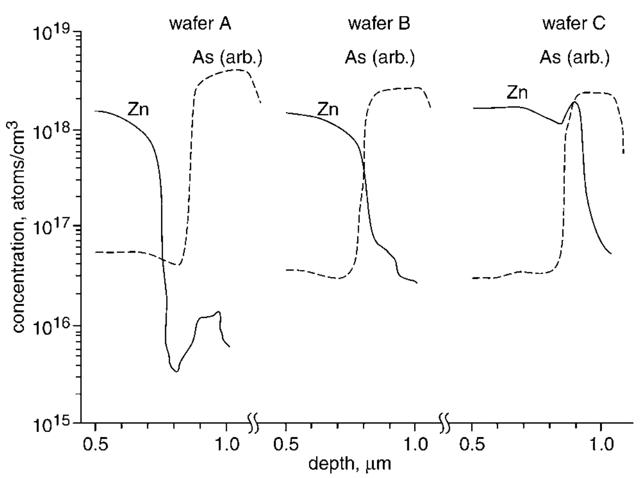

Fig. 1 *Zn concentration depth profiles near InGaAsP MQW region for wafers A, B, C*

The 1.3 µm InGaAsP *pin* structures investigated in this study were grown by low pressure (60 torr) metal organic vapour phase epitaxy and consisted of 7 nm–1% compressively strained wells separated by 10 nm lattice matched barriers. The MQW region is surrounded by symmetric, not intentionally doped separate confinement (SCL) layers and *p*- and *n*-doped cladding layers. An electron collector was also grown on top of the laser structure so that one can measure leakage of electrons from the active region by an electrical technique [3, 8]. Secondary ion mass spectrometry (SIMS) concentration depth profiles for Zn, which show the different doping profiles near the heterointerface, are shown in Fig. 1; the arbitrary As signal is simply intended to denote placement of the MQW active region. The SIMS data, as well as leakage and threshold current density data from [3], are summarised in Table 1. The Zn concentration at the heterointerface is also included. An accurate description of the Zn profile is represented by the setback, which is the distance between the *p*-doping profile edge at a Zn concentration of 5×10^{17} cm^{-3} and the *p*-cladding/SCL interface. Positive setback values mean that the Zn profile is set back from the heterointerface while negative values imply that the Zn profile lies within the active region. MQW layer photoluminescence was excited by a chopped YAG laser (1064 nm), and the PL was collected by a 1 m spectrometer and Ge detector. The PL intensity against excitation power was measured at 77 and 300 K.

Table 1: Summary of SIMS Zn doping profiles and device characteristics

Wafer	Setback (nm)	Zn_{HI} (10^{18}/cm^3)[a]	J_L (A/cm^2)[b]	J_{th} (kA/cm^2)[b]
A	147	Undoped	22.5	2.2
B	12	0.3	12	1.6
C	−47	2.0	2.5	2.7

[a]Zn concentration at heterointerface
[b]From [3]

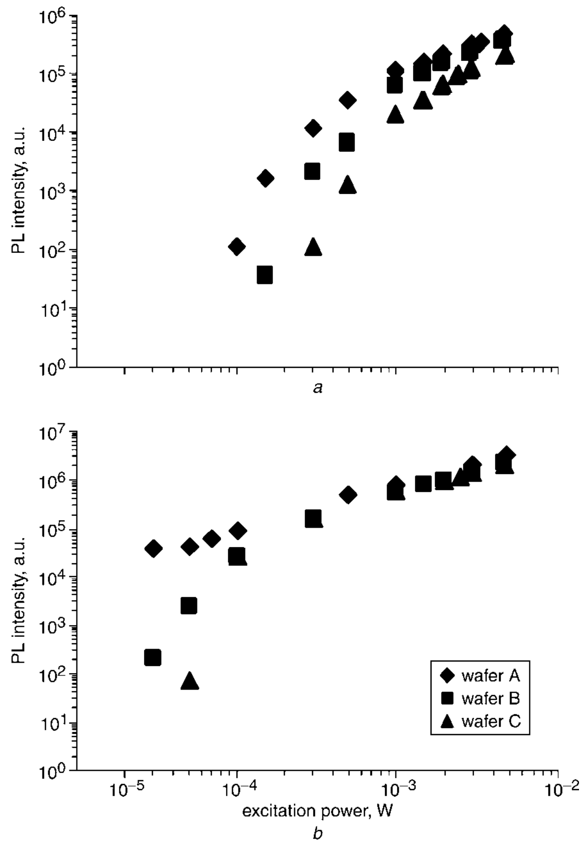

Fig. 2 *Excitation dependence of PL intensity at 300 and 77 K for wafers A, B, C*

Fig. 2*a* shows the PL intensity against excitation power at room temperature (300 K) for wafers with undoped (A) and moderately doped (B) heterointerfaces and from one with a doped SCL (C). The behaviour of the PL intensity is identical for all three wafers, superlinear at low excitation and then linear with higher excitation powers. At low excitation power, it has been previously explained that the PL intensity is limited by surface recombination at the perimeter of the *pn* junction and/or by lateral spreading of photoexcited carriers [7]. In addition, it is readily observed that wafer A with an undoped HI has the highest PL intensity for all excitation powers while wafer C with a doped SCL has the lowest. When the temperature is reduced to 77 K (see Fig. 2*b*), wafers B and C with a moderately doped heterointerface and doped SCL, respectively, continue to have a superlinear and then linear behaviour with increasing excitation power. However, the behaviour of wafer A has become linear for all excitation powers. This behaviour is consistent with that expected for an isotype structure [7]. Although we do not have an isotype structure, the *pn* junction has been displaced from the MQW active region into the cladding layer on the *p*-side of the active, which is responsible for the linear behaviour at the lower temperature in Fig. 2*b*. Since the linear behaviour in wafer A at 77 K was not observed at room temperature, it is suggested that there was an additional, unknown acceptor near the heterointerface which froze out as the temperature was reduced. At room temperature, the concentration of this acceptor was sufficient to maintain the *pn* junction near the active region, giving rise to the superlinear and linear behaviour observed.

As the Zn profile penetrates into the *i*-InGaAsP MQW region, the electric field associated with this region increases because the effective width of the *i*-region has decreased [9]. Thus, it is anticipated that the electric field from the MQW active increases in the order $A \rightarrow B \rightarrow C$, which seems consistent with the excitation dependence of the PL intensity. The presence of the larger field in wafers B and C should sweep carriers to the perimeter more rapidly than A, and thus this suggests that superlinear behaviour should be observed at low excitation, as observed for B and C, while linear behaviour is observed for all excitation powers in A at 77 K.

In summary, we have shown that the excitation dependence of the photoluminescence intensity is a sensitive indicator of the placement of the *pn* junction in multi-quantum-well InGaAsP laser structures. A superlinear dependence of PL intensity on excitation power is an indication of a double heterostructure where the *pn* junction is in the active layer or at the heterointerface. However, a linear behaviour is suggestive of a heterostructure with a displaced junction. Thus, PL excitation dependence can serve as a non-destructive tool to qualify wafers before processing.

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